New Keck Spectra of Q0014+813: annulling the case for high deuterium abundances

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ABSTRACT

The spectrum of quasar 0014+813 was the first in which deuterium was claimed to be observed, at first as a probable detection, and later "confirmed". It is important because it is the only case in which there is a serious likelihood of a high D/H ratio, since the others are more ambiguous and admit a wide range of D/H including zero. We present new high-resolution spectra with higher quality than those published. Deuterium has been reported in two Lyman limit systems (z_{abs}= 3.32, 2.80) along the line of sight. In both we find that the absorption is readily explained by H alone and that deuterium absorption is neither required nor suggested by the spectra. The three previous models with high D/H values (D/H $\approx 20 \times 10^{-5}$) are not compatible with the new data, and in some cases the differences are surprisingly large. Since the spectrum is compatible with all values of D/H from zero up to large upper limits, neither absorption system can be used to measure D/H, and previously cited values should be disregarded. There is now no case in which a high value of D/H has been established, and all data are compatible with low D/H. Deuterium has been seen and measured in only two QSOs (Q1937–1009 and Q1009+2956), both of which give low D/H. Several other QSOs give upper limits which are about ten times less sensitive.

1. HISTORY OF Q0014+813

Q0014+813 is a bright (V = 16.9), high redshift (z_{em} = 3.37) quasar, which has been well studied since its discovery in 1983 (Kuhr et al. 1983). Measurements of D/H have

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been claimed in two absorption systems towards this QSO. The first, at z_{abs}= 3.32 has been discussed in three observational papers, and is by far the best case for high D/H. This Lyman limit system is also known to be very metal-poor (Chaffee et al. 1985, Chaffee et al. 1986).

Songaila et al. (1994, hereafter SCHR) observed this QSO with the Keck-1 telescope and the HIRES spectrograph. They found an absorption line near the expected position of deuterium, but could not constrain the model fit, and only reported an upper limit, D/H $< 25 \times 10^{-5}$. The portion of their spectrum around D (their Figure 3) appears to be smoothed, as can be seen from the strong correlations in the counts of adjacent pixels. They do not mention smoothing and quote the nominal HIRES resolution of R=36,000. Rugers & Hogan (1996a, hereafter RH) state that SCHR did smooth the data.

Carswell et al. (1994, hereafter CRWCW) analyzed the same absorption system with lower SNR spectra from the echelle spectrograph on the KPNO 4m telescope. They showed that many different models could be applied to their data, and found D/H $< 60 \times 10^{-5}$. The models of SCHR & CRWCW are consistent with earlier studies by Chaffee et al. (1985, 1986). In particular, there was excellent agreement on the total hydrogen column density, both SCHR and CRWCW gave Log N(H I) = 16.9 cm^{-2}, and Chaffee et al. (1985) gave Log N(H I) = 16.8 cm^{-2}.

RH re-reduced the SCHR spectrum using the standard IRAF package. They did not smooth the data, and saw a strong "spike" (3 pixel region of increased counts) in the deuterium absorption feature. They considered this real, since the top of the spike was 6 – 7 σ above the bottom, and it was also seen when the data were reduced using the SCHR software. They devised a new model with two D components, one on either side of the spike. The H must then also be split into two. They increased the total N(H I) column by 70% to Log N(H I) = 17.2 cm^{-2}, outside the ranges of both previous studies. RH reported that the new model gave a direct measurement of D/H in both components, which is surprising, because the complexity and number of free parameters was higher than in all previous models. They found D/H = $19 \pm 5 \times 10^{-5}$ in each component.

In this paper, we present new HIRES spectra of Q0014+813, which has the highest resolution and SNR to date. We compare our data and model fits with those of SCHR, CRWCW & RH and show that D/H cannot be measured in this system.

Rugers & Hogan (1996b) noticed that a second higher column density system with Log N(H I) > 18 cm^{-2}, at lower redshift, $z_{abs} = 2.80$, contained unusually narrow and unresolved metal lines. They obtained a measurement of D/H with only the blue wing of the Lyα line where D was not even resolved. They argued that the steepness of the line

required a fit with D. We show that this is incorrect. The fit with D is not unique and cannot constrain D/H.

2.   OBSERVATIONS & DATA REDUCTION

On the nights of Nov 2nd & 3rd, 1996, we used the HIRES spectrograph (Vogt 1994) on the Keck-1 10-m telescope to obtain spectra of Q0014+813 in four separate exposures totaling 4.5 hours. Each of the four spectra provided wavelength coverage of 3700 to 6100 Å, although the useful portions of the spectra only extend down to about 3900 Å. The first three exposures were taken with a 0.8" x 5.0" slit, which gave a resolution of 6 km s^{-1}. With the fourth exposure, we used a wider slit (1.45" x 5.0") to reduce slit losses, which gave a resolution of 10 km s^{-1}. The newly commissioned HIRES rotator (Tytler et al. 1997) was used during all observations to minimize losses due to differential atmospheric diffraction; losses which can be substantial below about 4000 Å. The spectra were optimally extracted with the automated program described in Burles & Tytler (1996). For wavelengths above 4100 Å, we added only the 3 higher resolution spectra and not the fourth one, which would decrease the spectral resolution. Below 4100 Å, the lower resolution spectrum was coadded to increase the SNR. First we convolved the higher resolution spectra with a gaussian to match the low resolution spectrum, and then we coadded all 4 spectra. The final spectral resolution, which we need to find intrinsic line parameters, was measured from the arclamp line widths. All wavelengths are vacuum values in the heliocentric frame.

3.   MODEL FITS

There are several "rules" which we use to assess fits. We discuss model fits of Lyman limit systems and other D/H techniques in more detail in Tytler & Burles (1996).

(1) Model fits do not need to explain all of the absorption in a region of the spectrum, since there is often additional unrelated H absorption, which may have no effect on the parameters of interest. (2) Fits must never absorb flux which is seen. This would be unphysical, and would immediately rule out a fit, provided the "flux" was real and not noise. (3) The best model is the one which uses the least number of parameters to fit the data. This usually means the least number of velocity components. (4) A model fit should give a reasonable chi-squared statistic ($\chi^2 \approx 1$) if all absorption in the spectrum is included in the model. (5) Noise can be judged from the fluctuations in the bottom of the saturated H lines, which should have exactly zero flux when there is no noise, no sky subtraction

errors and no stray light. (6) When the signal to noise is high, we need full page plots which show the noise level and each pixel, to see if fits are acceptable. Fits which differ from the data by 5% are rejected with SNR =100. (7) A complete model would account for all data on an absorption system. (8) All lines and continuum absorption from a given ion should be fit with the same parameters (b, N and z). (9) Different ions may require different parameters (b, N and z). (10) Wherever we see metal lines we expect to see H lines, but the parameters (z, b) may appear to differ if there are hidden unresolved components eg. with different metalicity and ionization. (11) The absolute values of line widths should be physically reasonable, e.g. $b > 15$ km s^{-1} for Log N(H I) > 16 cm^{-2}. (12) The ratio of b values should be physically reasonable. The line widths arising in a single absorber should be fully described by a temperature and a turbulent velocity. (13) A line is unlikely to be D if we find that we can not fit it using only D plus the blend with its own H. When additional absorption (e.g. H at another velocity) must be introduced, it is generally possible to fit the whole line with this new H. We can then have any D/H from zero up to some upper limit.

4. ABSORPTION SYSTEM at $z_{abs} = 3.32$

Figure 1 shows a region of the spectrum containing the saturated Lyα absorption feature at z_{abs}= 3.32. The absorption line at 5251.45 Å, identified by SCHR, CRWCW & RH as possible D absorption, is marked by the left tick mark in Fig. 1. The position of the associated H absorption is shown with the right tick mark near 5252.88 Å. To determine if the line at 5251.45 Å is D, we start with the following: the line has a column density of Log N = 13.50 ± 0.03 cm^{-2}, a velocity dispersion of $b = 24 \pm 1$ km s^{-1}, and a redshift of $z = 3.320976$. For the rest of this letter we will refer to this redshift as $v = 0$ km s^{-1}, and refer to all other line positions as velocity displacements from this redshift. The position of this line is very well determined and optimally fit with a single component at $z = 3.320976 \pm 0.000007$ (± 0.6 km s^{-1}).

We must now determine the properties – most importantly the positions – of the H I absorbers. The Lyβ,Lyγ, & Lyd transitions show that there are at least two components (see Figure 2), which we refer to as the blue (A: $v \simeq 10$ km s^{-1}) and red (B: $v \simeq 120$ km s^{-1}) components. These components are well separated, by about 108 km s^{-1}. They are not the close components considered by RH which were both near 0 km s^{-1}. For a D/H measurement the only important information comes from the absorber or absorbers in the blue component, because the D from the red component would be in the bottom of the saturated Lyα line where there is no flux.

The blue side H absorption at $v \simeq 0$ can be fit reasonably with one H I absorption

component (A in Fig. 2a), That absorber has Log N(H I) = 16.7 cm^{-2}, b = 23.8 kms, and $v = 10 \pm 0.5$ km s^{-1}. The large velocity offset is the main reason why D alone can not explain the absorption feature at 5251.45 Å. There must be significant additional absorption, e.g. by H. For this reason, we conclude that if the blue side H I absorption contains only one component, this system is unsuitable for a D/H measurement. At best we get a high upper limit, which still allows D/H = 0.

Table 1 shows goodness-of-fit values for each model presented. We show reduced χ^2 values over critical regions in the spectrum. The best fit is found by minimizing the total reduced χ^2 of all the Lyman lines. Fits are acceptable when the reduced reduced χ^2 is about one. In Table 1, we show only the regions that are most sensitive to the position and column density of D. The 1 component model is particularly bad on the blue side of H I Lyα around –40 km s^{-1} $< v <$ –60 km s^{-1}.

A much better fit is obtained with two components (B and C in Figure 2b), which is the maximum number justified by this spectrum. The stronger H I component (C) is at $v = 17 \pm 1$ km s^{-1}, with Log N = 16.61 ± 0.05 cm^{-2} and $b = 19 \pm 1$ km s^{-1}, and gives a better fit to the high-order Lyman lines (i.e. Lyman 13-17). With component C in this position, the second component B is needed to fit the low order lines. Because the best evidence for component B comes only from saturated regions of absorption (Lyα through Lyδ), we find that it is not well determined – many different N, b, and v values for component E give a good fit to the data. The best fit occurs for Log N = 16.12 cm^{-2}, $b = 17$ km s^{-1}, and $v = -13$ km s^{-1}. Once again, because both of the H lines are far from the $v = 0$ required to fit D, the feature at 5251.45 Å can not all be D. In Figure 2b we model all of the 5251.45 Å feature as a single unassociated H line (component H) with Log N(H I) = 13.52 cm^{-2}, $b = 24$ km s^{-1}, $z = 3.319799$, and $v = -81$ km s^{-1}. The reduced χ^2 on the blue side of Lyα is ≈ 4, which indicates that the model fit could still be improved between –40 to –60 km s^{-1}. In Ly-10 & Ly-13, the reduced $\chi^2 \approx 2$ results from extra Lyα absorption which we have not included in the model, This unrelated H I absorption does not affect the results and would only complicate the models presented here.

Figure 2c shows the best fit which we can obtain if the core of the 5251.45 Å feature is the D of component E. Here we have moved component B (Fig. 2b) to a higher velocity to better match 5251.45 Å . This fit is unacceptable because the blue side of Lyα gives χ^2 = 11.9. It is also an unusual fit because the D absorption is strongest in the –4 km s^{-1} component (E), while H is strongest in the +16 km s^{-1} component (F), so that the D/H values in the two components to differ by a factor of 30. The feature is fit by a blend of D absorption from E and F, and because there are many possible values of $v(E)$, we can not measure D/H in either component. Even if move component E around to best fit

5251.45 Å, we do not get acceptable fits because the same gas must explain the blue side of Lya (at –40 to –60 km s^{-1}).

Regardless of how the blue side H I absorption is fit, as one component or as two, the 5251.45 Å absorption feature requires the presence of interloper absorption. Because an interloper *can* explain all of the absorption, and we know that one *must* be present, no measurement of D can be made in this system. Because we have the highest SNR observations to date of this object, we conclude that all previously published D/H measurements in this object are incorrect. We also conclude that no measurement of D/H in this system can be made in this system.

4.1.   Other published models of z_{abs}= 3.32

Three previous models have been published for this absorption system, and we have discussed them briefly in I. The first two studies concluded with best fit values of D/H with no formal limits (SCHR & CRWCW), and the third (RH) claimed to measure the same D/H in each of two components. We now compare the best models form each study with the new spectrum.

There are considerable differences in the continua levels. In Figure 4 we show our continuum level fit to one echelle order. We see that a slowly changing smooth (third order) function gives an excellent fit to the high points, which are known from many other studies to be the continuum. There is no need for small scale irregularities. The continua in two other studies can be deduced by tracing the normalized flux published in each study and applying it to our spectrum. For example, at every pixel where the normalized flux is unity in a published spectrum, the corresponding continuum level in our spectrum must equal the flux in that pixel. The SCHR continuum is concave and drops below ours by 14% , they assume little or no absorption in the peaks between the lines near 5246, 5257 and 5259 Å. CRWCW continuum is approximately constant and low by about 9%. This looks like a reasonable continuum based on the restricted wavelength coverage they present in their Figures 1 & 2. Although both continua have surprisingly large errors, the continuum level is not as important as the velocities.

There are also large differences in velocities. CRWCW find D at $v = +8$ km s^{-1}, a good agreement with our wavelength scale and spectrum because this is an "external" absolute error. SCHR quote D at $v = -75$ km s^{-1}. Most of this error is removed if we assume that they forgot to correct their data to vacuum wavelengths. With this correction their D is at $+8$ km s^{-1}. If they did not apply a heliocentric correction then their D would

be at $+4$ km s^{-1}. We do not understand the wavelength calibration of RH, but we find a mean velocity difference of $v = -23$ km s^{-1}. Since all three papers have zero-point offsets in the wavelength scale, we now apply small velocity shifts to give their models the best fit to our data.

SCHR use a five component model, with only one strong blue H I component at $v = +4$ km s^{-1} (Fig. 3a). The H I component is too red in Lyα, Lyβ, but too blue in Ly-13. This model uses D/H $= 25 \times 10^{-5}$, and assumes b(D I) = b(H I) / $\sqrt{2}$. The amount of absorption is no where near sufficient to account for the whole feature at 5251.45 Å, so we must conclude that interloping absorption is necessary for the SCHR model to give an adequate fit.

CRWCW also model the H I with one strong blue component, but they add two weak H I absorbers near the D position (this absorption is blended with the D line). The fit by CRWCW is by far the best fit of the 3 different prior studies, even though they had much lower quality data than SCHR & RH. CRWCW made very conservative conclusions, which we confirm: *We reiterate that no single measurement ... should be regarded as providing anything other than an upper limit... The results here should be confirmed (or not) and improved by obtaining and analyzing high S/N, high resolution spectra.* We show only one of the models proposed by CRWCW, with D/H $= 24 \times 10^{-5}$ (see Fig. 3b). Their full range of models allowed D/H as high as 60×10^{-5}.

RH model the H I with two strong blue components with positions separated by 21 km s^{-1}. The mean velocity position of the two components is -1 km s^{-1}. The two components were demanded not by the structure of H I in the high-order Lyman lines, but by the spike in the spectrum which split the deuterium feature in two. This spike left two very narrow $b < 9$ km s^{-1} lines, which were they assumed *a priori* to be deuterium. We have four separate spectra of Q0014+813, and this spike appears in none of them. RH stated that the spike must be real because it also appears in the data of SCHR. Our higher quality spectra show that the spike is not real.

Amazingly RH were able to make two *independent* measurements (each accurate to 30%) of D/H which agree exactly. RH analyzed the same data that allowed SCHR to quote only a best guess. Figure 3c shows the dual component model proposed by RH, which is nothing like the data (see Table 1). In addition, the H I column density was overestimated by more than 50%. The fit to Ly-13 shows that this is a very major error, which is easy to see. Tytler & Burles (1996b) have previously noted this problem: the RH fit could be seen to unphysical because it absorbed flux where light was seen in their Figure 2. To compensate for their overestimation of N(H I), and to allow a fit to Lyα, RH required extremely low velocity dispersions for H I. One blue component is modeled with $b = 10.1$

km s^{-1}, which corresponds to a cloud temperature of $T < 6500$ K. No Lyα absorber with Log N(H I) ≈ 17 cm^{-2} has ever been measured with such a low velocity dispersion. The RH fit to this system is unphysical and seems to have been designed to give a high D/H fit.

There are at least two possible origins for the "spike". SCHR applied a filter to remove cosmic rays (CRs), but we see four large spikes in the top panel of their Figure 1 (5224, 5232, 5239, 5256), which look like CRs, and might account for the spike at the D position. RH used the IRAF IMSUM procedure, which they note left some CRs. There are also hot pixels on the HIRES CCD, each of which should be flagged because they are not removed or revealed by normal data reduction.

4.2. Conclusions on $z_{abs} = 3.32$

We conclude that most of the H I is at 9 km s^{-1} $< v < 18$ km s^{-1}, and not at $v = 0$ where it should be if the 5251.45 Å feature is D. If there is D in 5251.45 Å then at least one additional line is needed to give a fit: either an interloper if H is one component, or D from component F if H is two component). There is no way to determine the position of this additional line, so the fit is ill-constrained and no D/H measurement can be made. Only weak upper limits can be placed on D/H in each component.

If we try to fit all of 5251.45 Å using D at the velocities of the two components (E & C) which best fit the H, then we get the result shown in Figure 2d, which is completely unacceptable, again because the velocities do not fit. But this models allows us to place 2σ upper limits on D/H of $< 100 \times 10^{-5}$ and $< 35 \times 10^{-5}$ for components B & C, respectively. The fit with these upper limits is shown in Figure 2d.

5. ABSORPTION SYSTEM at $z_{abs} = 2.80$

The spectrum we presented above also covers another Lyman limit system (at $z_{abs}=$ 2.80), in which another measurement of D/H has been made and published. Rugers & Hogan (1996b) analyzed this system with the same spectrum presented in RH. They concluded that the blue wing of Lyα must be D and found D/H = 19 $^{+16}_{-9} \times 10^{-5}$. Our new spectrum has the same wavelength coverage of the spectrum studied by Rugers & Hogan, so we can test the goodness and uniqueness of their model fits on our higher quality spectrum.

This system has a high neutral hydrogen column density, Log N(H I) > 18 cm^{-2}, determined by the opacity at the Lyman limit and the damping wings of Lyα. The hydrogen column density is divided among many components. The strongest of these

components have accompanying metal lines which allow accurate determinations of their velocity positions. The weaker hydrogen components will not usually have significant metal lines and then their positions can only be determined with the lines in the Lyman series. This presents a serious problem: because of the Lyman limit system at higher redshift and a steep decline in sensitivity as wavelength decreases, only the spectral region covering Lyα can be used to place constraints on the model for this system. Therefore, any information on the column densities and velocity dispersions of D and H must come from the Lyα feature alone.

The top panel of Figure 5 shows the large saturated Lyα feature at $z_{abs} = 2.80$. The tick marks indicate the velocity positions of the strongest components determined by the accompanying metal lines. Figure 5 also shows 6 of the metal line complexes associated with this system. Our data require at least 10 components for an acceptable fit to the metal lines (shown by the solid curve). The high number of metal line components introduces at least 20 free parameters to the model fit of Lyα.

Many of the metal lines have narrow intrinsic velocity dispersions, b $<$ 5 km s^{-1}, but the components are spread over a range of velocity, $\Delta V = 300$ km s^{-1}. The large velocity range is much greater than the velocity splitting of D and H (81.6 km s^{-1}), Only in the lowest velocity component (bluest component) could deuterium be detected. The bluest component has low velocity dispersions in the metal lines, b(Si) = 4.1 $\pm$0.5 and b(C) = 4.8 $\pm$0.5. The low values imply an upper limit to the temperature in this component, T $< 22,000K$, and also upper limits to the velocity dispersions of H and D: b(H) $<$ 19 km s^{-1}, b(D) $<$ 13.4 km s^{-1}.

Rugers & Hogan argue that the blue wing can only be fit with a very narrow line, too narrow for hydrogen. Our data show that this claim is false. If the line is placed at the expected position of D corresponding to the bluest metal component, then it must be (1) narrow, and (2) not completely unsaturated (see Figure 6a). The maximum line width is set by the metal lines, and the line can not be made narrower without reducing its N(D I) and hence its central depth.

However is this line is H it can be placed freely, and an excellent fit is found with an ordinary H line with Log N(H I) = 14.1 cm^{-2} and b = 21 km s^{-1} (see Figure 6b). The single H line provides a good fit to the data, and it lies 16 km s^{-1} redward of position expected for D in the H associated with the blue most metal component.

It is tempting to place an upper limit on D/H in the bluest component, but this would be a dangerous exercise. The D line accompanying the bluest metal component has a strong upper limit, Log N(D I) $<$ 13.8 cm^{-2}, but the column density in the corresponding H line

has no lower limit. The model of Rugers & Hogan constrains the bluest component to a column density, N(H I) = 18.04 ±0.12 cm^{-2}. The constraint comes from the damping wings of Lyα, but this fit is not unique and the data do not require a column density in this range. The column density in individual components is difficult to determine in saturated features, even with high SNR data (Tytler, Fan & Burles 1996; Wampler 1996). An upper limit on D/H requires a lower limit on N(H I), which can only be measured in the high-order Lyman lines.

We conclude that it is impossible to measure D in this system with only spectral coverage on Lyα. The D line must be resolved from the H feature to rule out contamination from other H lines. The model presented by Rugers & Hogan is ruled out at the 10σ level in our data, and cannot be considered a measurement of D/H.

6. CONCLUSIONS

New high resolution, high SNR spectra of Q0014+813, show the following:

1. Measurements of D/H cannot be made in either of the two Lyman limit absorption system towards Q0014+813.

2. The candidate D line at z_{abs}= 3.320976 cannot be properly fit without introducing contamination from other lines. The exact amount and nature of the contamination cannot be constrained and precludes any measurement of D/H.

3. The strong Lyα absorption at z_{abs}= 2.80 does not require D absorption, and gives the best fit in models with no deuterium. Lyα is the only Lyman line which constrains the column densities of the H components. Without high SNR spectra of the other Lyman lines, we cannot even place upper limits on D/H in this system.

4. The only published measurements of high D/H are towards Q0014+813. The analysis we present here removes any suggestion of high D/H in QSO absorption systems.

5. Deuterium has been seen only twice in QSO absorption systems. In each case, we obtained a measurement of D/H (not an upper limit), because the D line can be fit by the velocities determined from metal lines, the D line widths agreed with predictions from the metal and H lines, and we applied statistical corrections for contamination by H. The first measurement of D/H in a QSO absorption system was made towards Q1937–1009 (Tytler et al. 1996), and the second towards Q1009+2956 (Burles & Tytler 1996). Both measurements give low values of D/H, which agree to within 15%. All other cases are upper limits, because of either poor data, or complex absorbtion systems which cannot yield strong constraints

on D/H. All data in QSO absorption systems are fully consistent with low D/H.

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Figure 1: The Lyα feature at z_{abs}= 3.32 in the Keck HIRES spectrum (FWHM = 6 km s^{-1}). The left tick marks the centroid of the line at 5251.45 Åand the candidate for D absorption. The right tick marks the position of the associated H line. We set these positions to zero velocity for the remainder of the analysis.

Figure 2: The Lyman lines of the z_{abs}= 3.32 system. In all of the plots the tick marks correspond to the line centers of individual components used in the model fits. We present 4 different fits to the data to investigate the possible models which could give an adequate measure of D/H. None of the models succeed in giving a measurement. The SNR in each panel is 55, 20, 17, 13, and 10 per 2 km s^{-1} pixel for Lyα, Lyβ, Lyγ, Lyd, and Ly-10 and above respectively. See the text for the descriptions and interpretations of each model. For Ly-10 to 17 we see absorption from more than one series line in each panel: e.g. velocity –40 km s^{-1} in Ly-16 is also +66 km s^{-1} in Ly-17. Each tick marks the position of a hydrogen or deuterium Lyman line. In the higher order lines, the components of the Lyman series begin to overlap, and the model profile becomes more complicated.

Figure 3: Four of the Lyman lines shown in Fig. 2. The models shown in these 3 plots are from other published studies of this system. We overlay the fits on our higher quality spectrum to provide a direct comparison of the different models. In Table 1, we quantify the goodness-of-fit of each model to the spectrum.

Figure 4: Comparison of Continuum Levels. The Lyα feature at z_{abs}=3.32 is centered near 5254 Å. The histogram shows counts from one of our four new spectra. These are "raw" counts, which have not been flux calibrated. Our continuum is the solid smooth curve which lies high on the data, because there is a lot of Lyα absorption at $z > 3$. The dashed line shows the fit that would be required to give the normalized spectrum in SCHR. The dotted line is an approximation to the fit required to give the normalized spectrum in CRWCW.

Figure 5: The Lyα and metal lines at z_{abs}=2.80. Zero velocity is set at the position of the bluest metal line. The fit to Lyα was produced from the model of Rugers & Hogan (1996b).

Figure 6: (a) The model fit of Lyα at z_{abs}=2.80 with an upper limit on N(D I). The lack of a lower limit on the corresponding H I column density prohibits any useful constraints on D/H in this system. (b) An extra H line gives a very good fit to the data and requires no D, and it does not fall at the position of D predicted by the bluest metal line.

Model	Figure	$\chi^2(\mathrm{Ly}\alpha)^{\mathrm{a}}$	$\chi^2(\mathrm{Ly}\text{-}10)^{\mathrm{b}}$	$\chi^2(\mathrm{Ly}\text{-}13)^{\mathrm{b}}$
1 Comp	2a	6.54	2.30	2.59
2 Comp	2b	3.87	2.29	2.14
2 Comp (force D)	2c	11.9	2.13	2.43
2 Comp (with D)	2d	75.2	2.29	2.14
SCHR	3a	171.6	4.04	5.77
CRWCW	3b	22.4	6.31	4.98
RH	3c	45.9	6.42	16.0

Table 1: Reduced χ^2 over important regions of the models

[a]measured over –100 km s^{-1} $< v <$ –40 km s^{-1}

[b]measured over –40 km s^{-1} $< v <$ +60 km s^{-1}
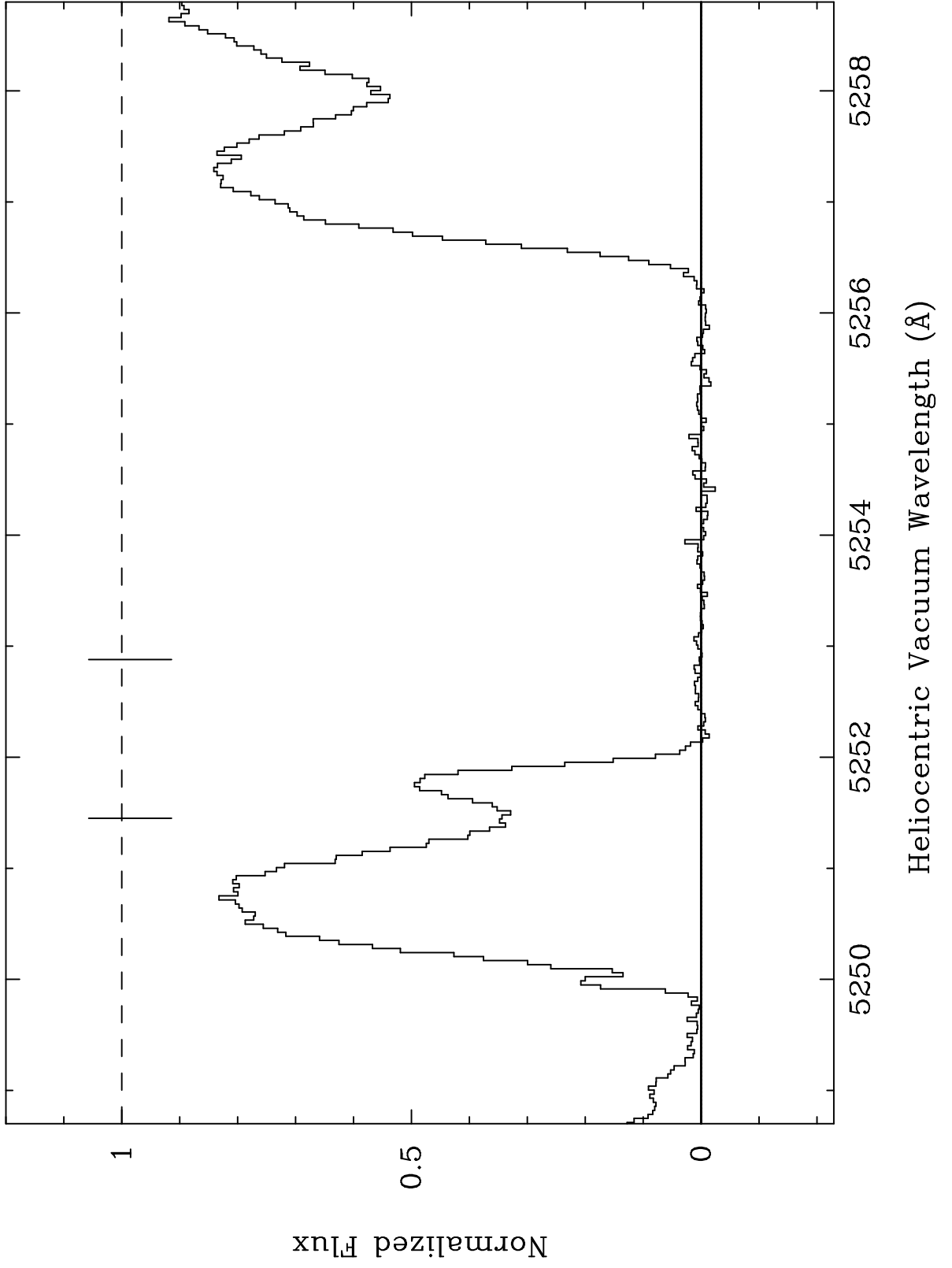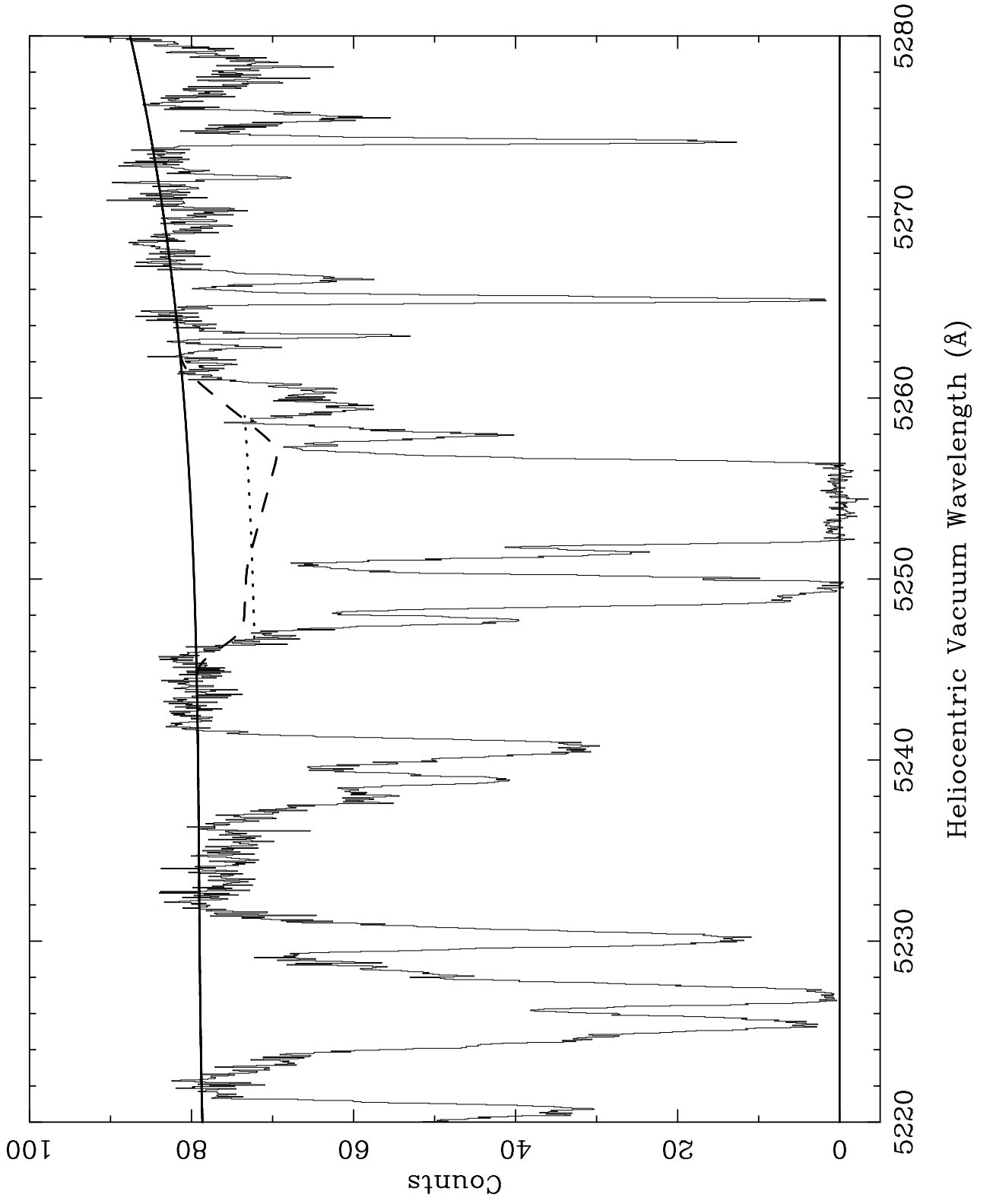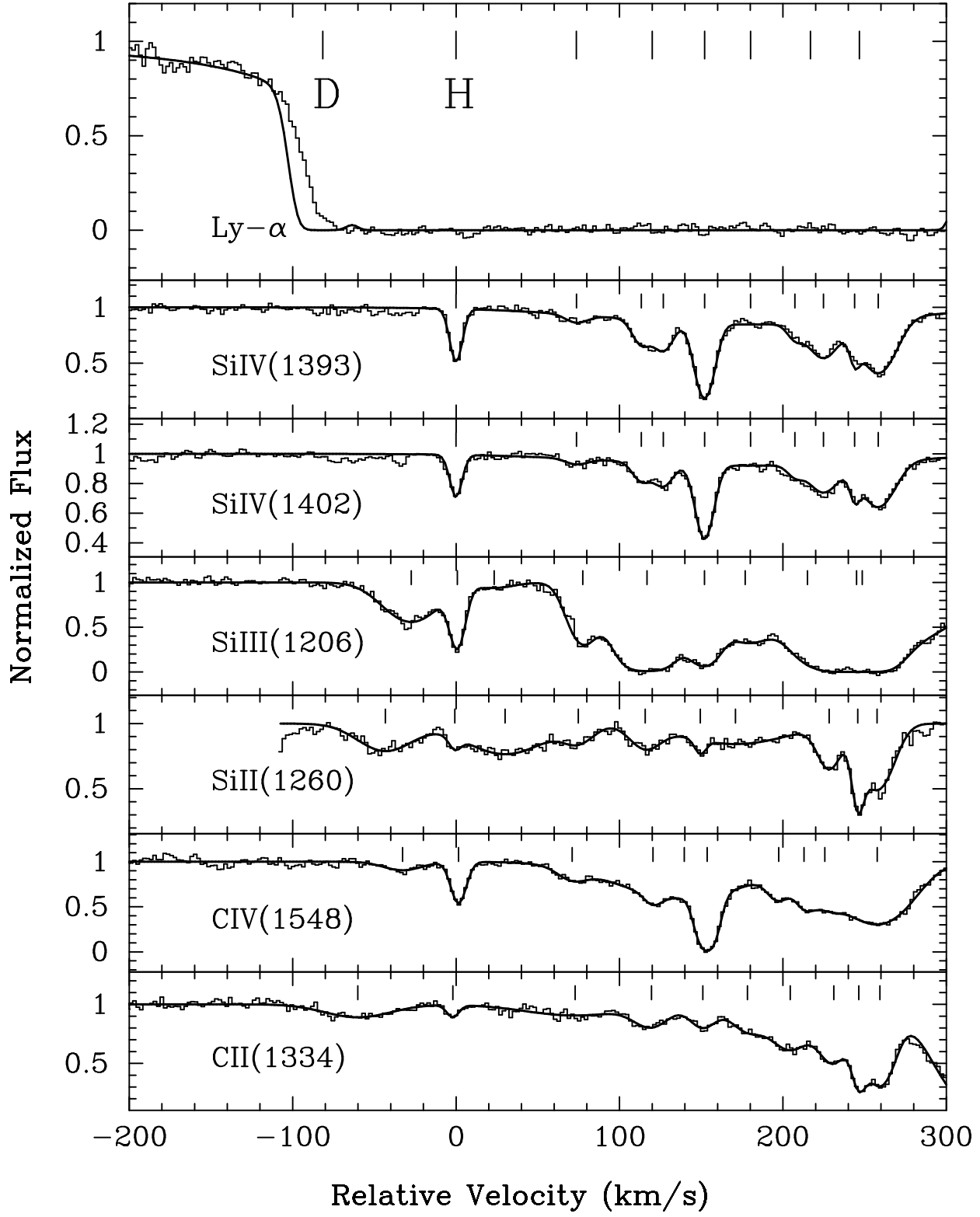
Fig. 1.—
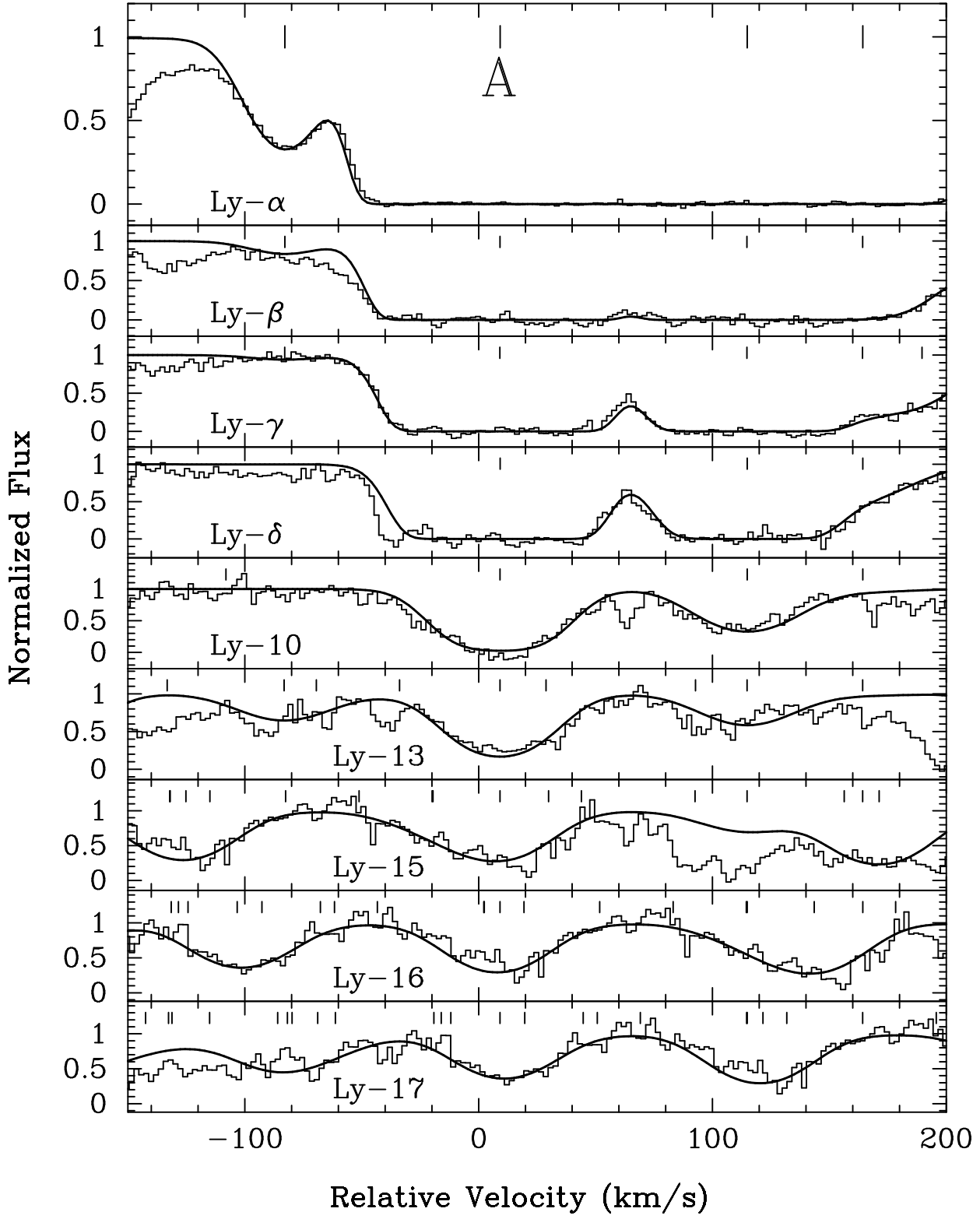
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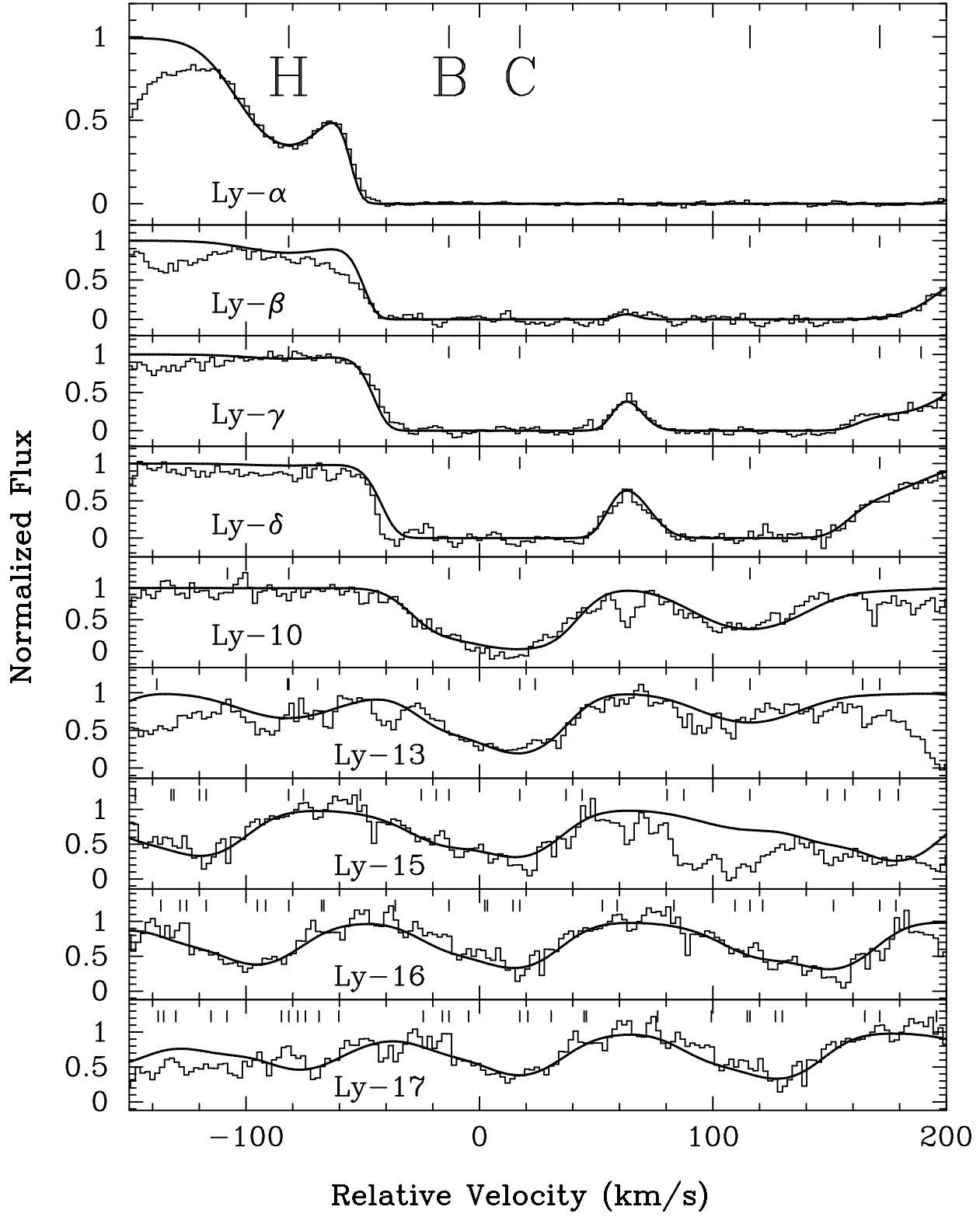
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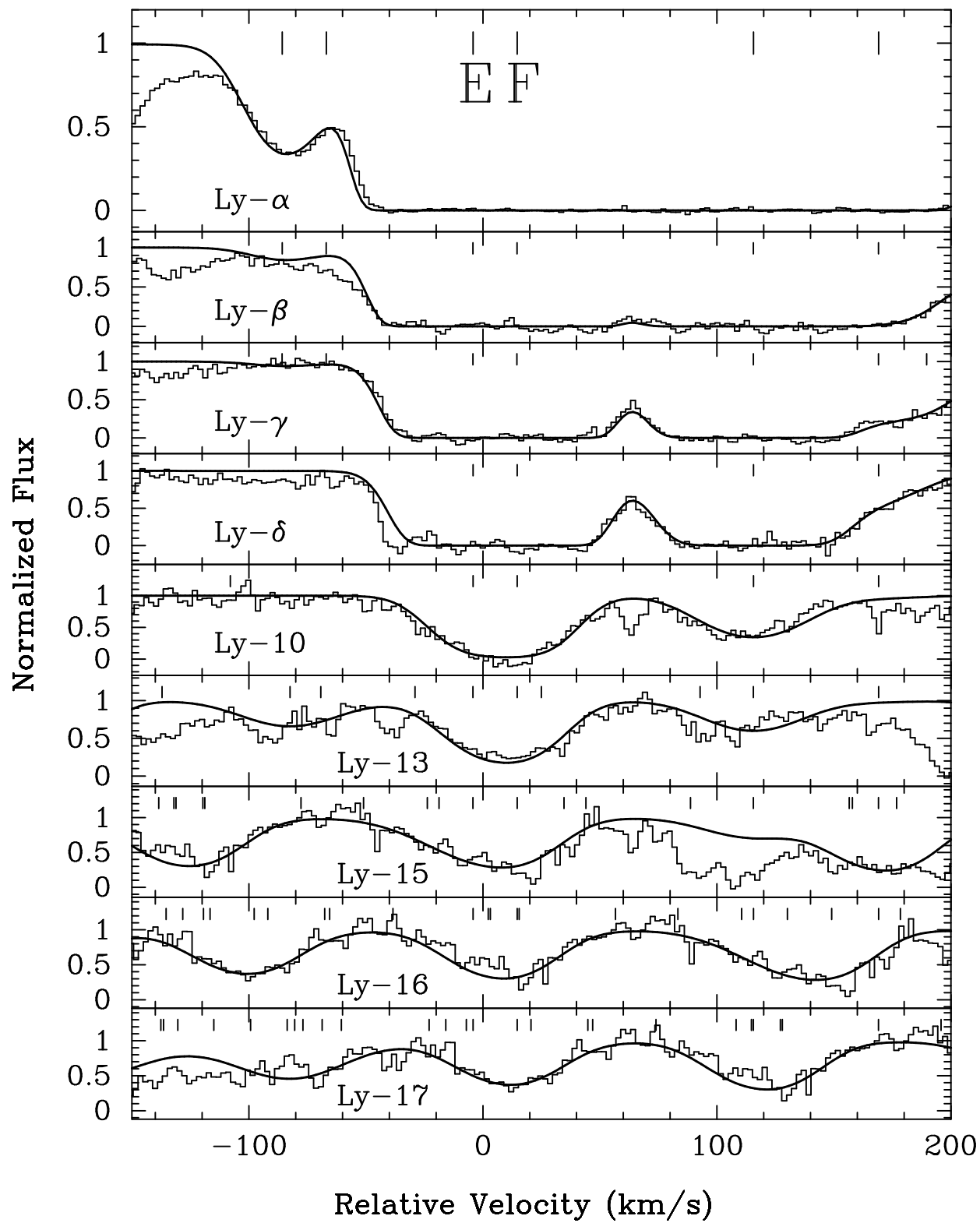
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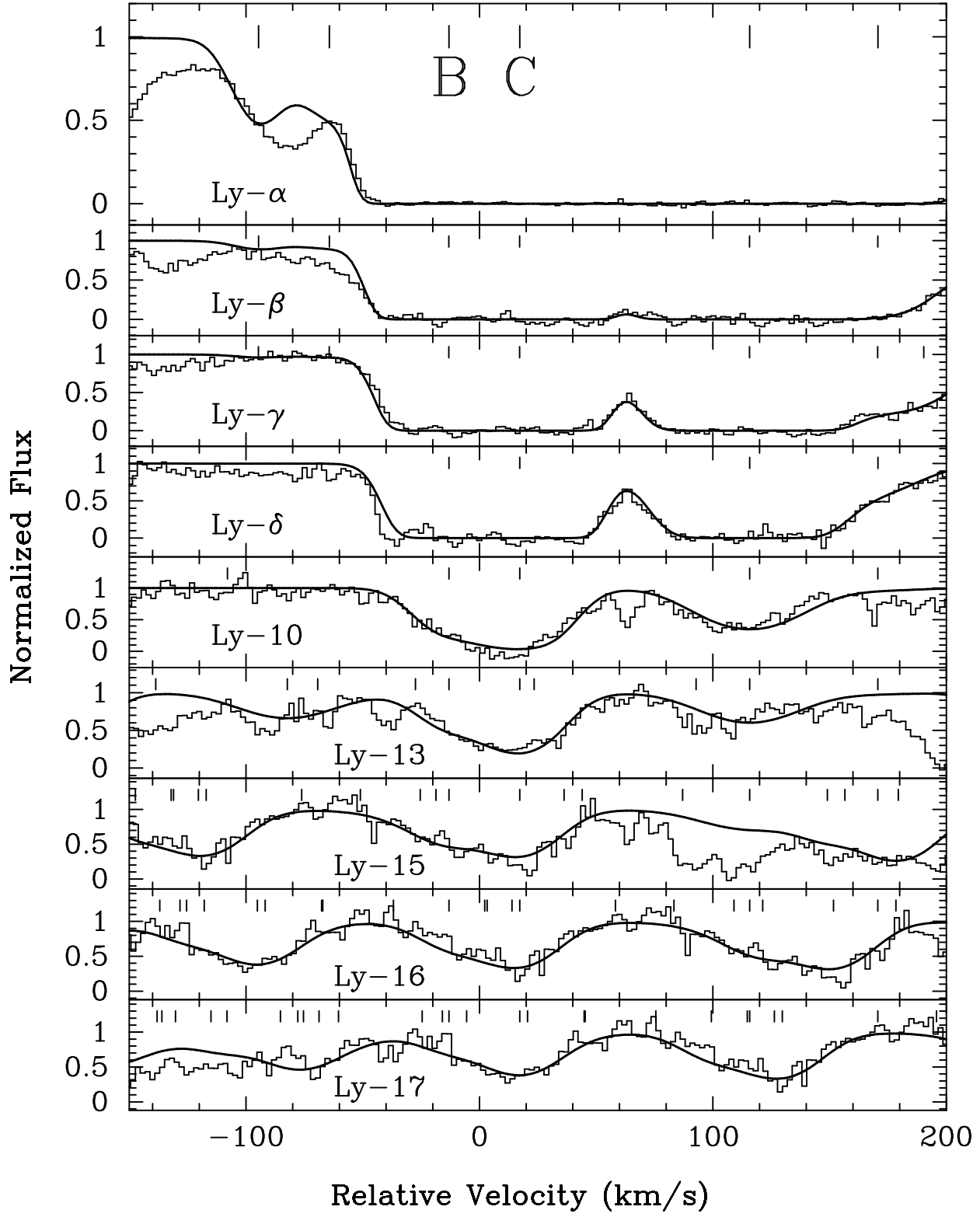
Fig. 2d.—
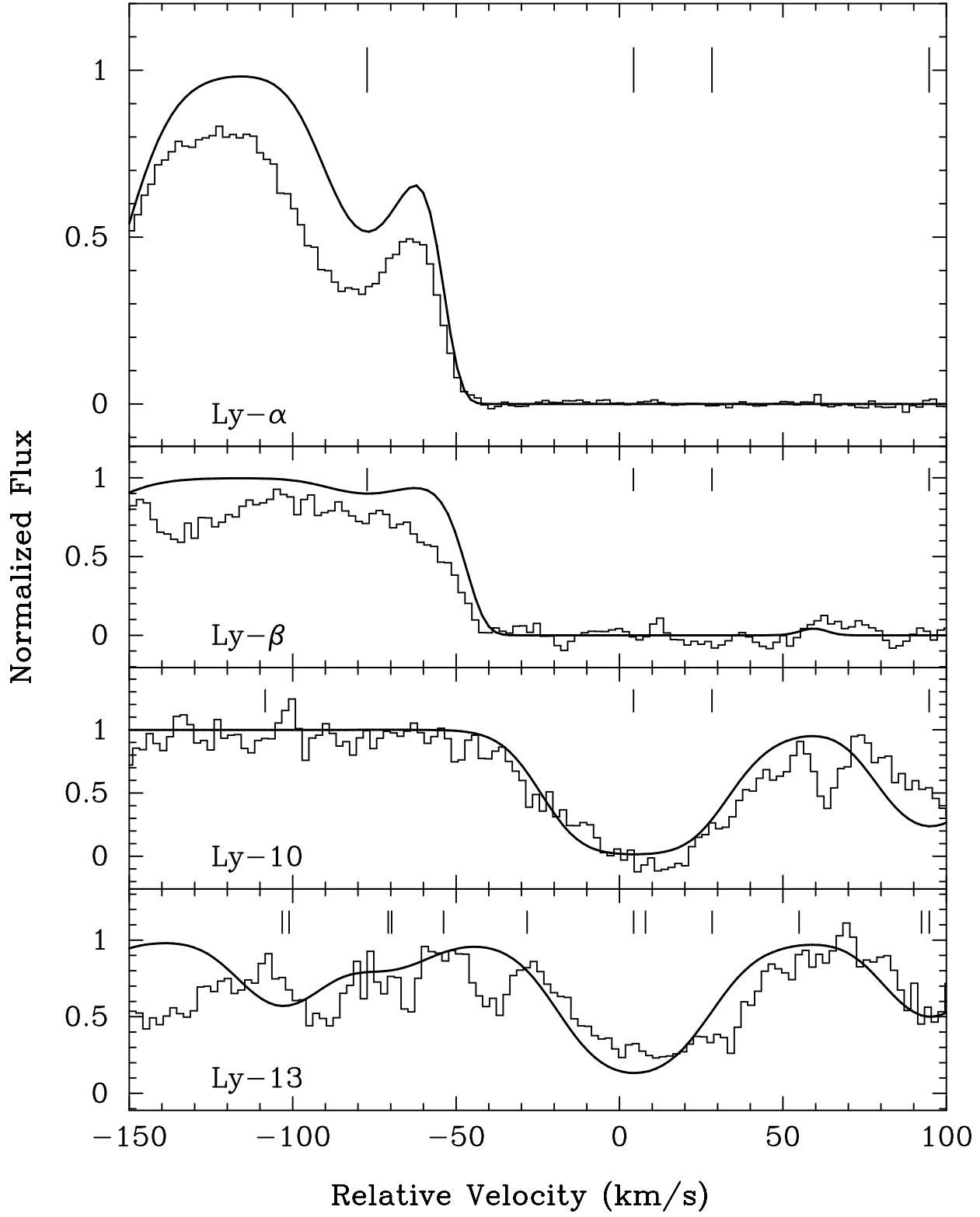
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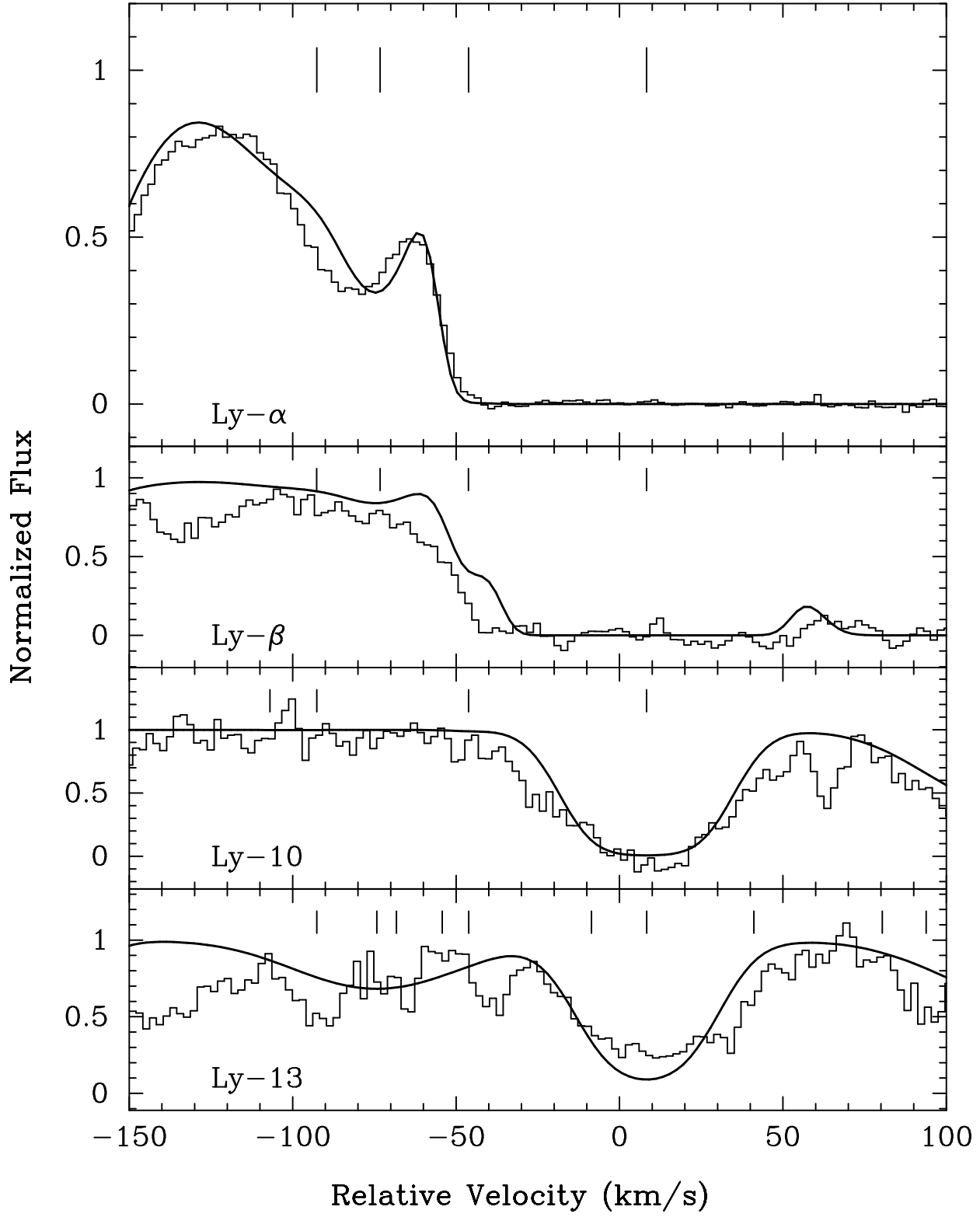
Fig. 3b.—
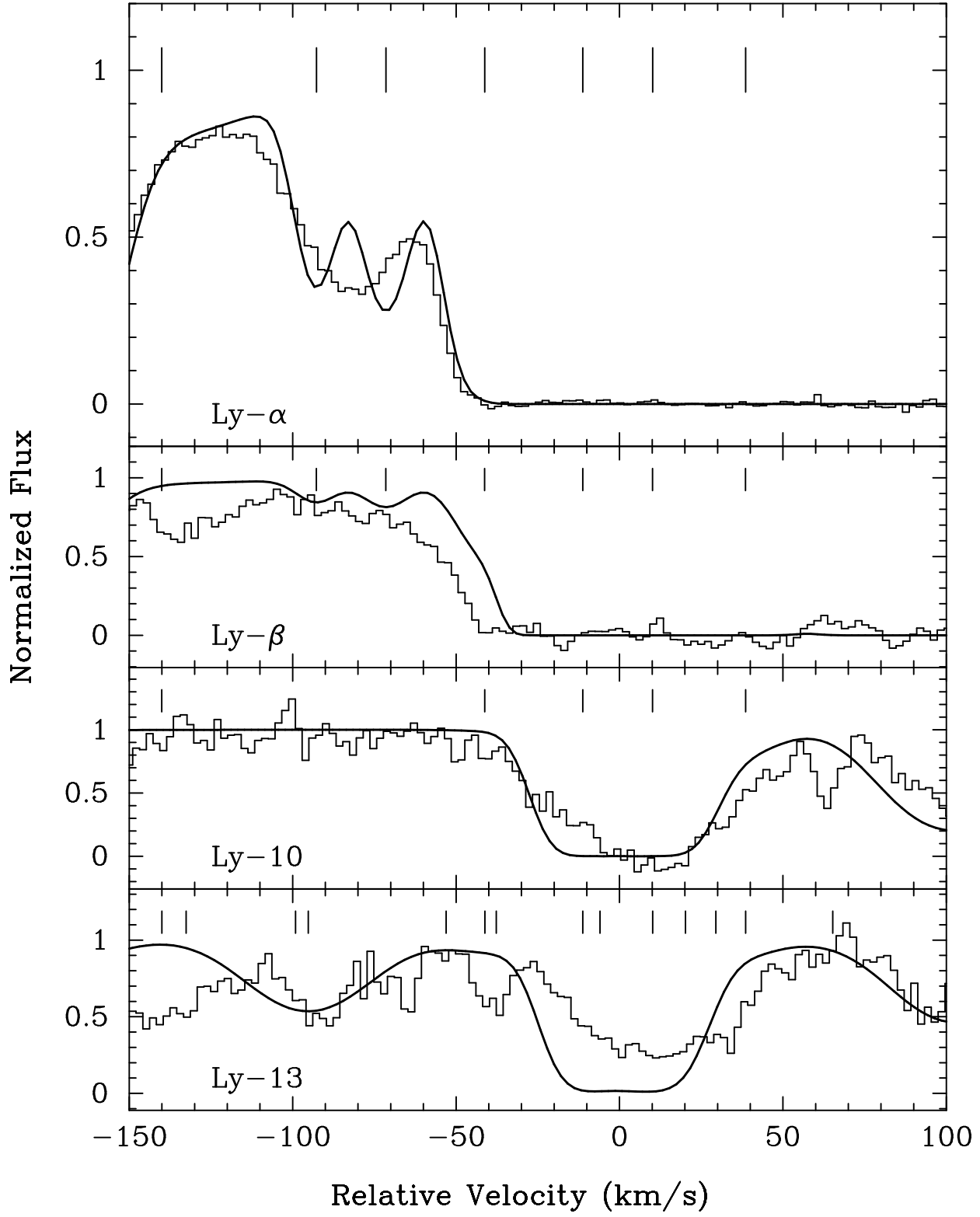
Fig. 3c.—

Fig. 4.—

Fig. 5.—

Fig. 6a.—

Fig. 6b.—